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METHODS FOR DETERMINING CRACK DEPTH*

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With the growing progress and applications of fracture mechanics, determination of the actual depth of a crack in a workpiece is required. Some methods for determining crack depths with ultrasonics are presented.

Determination of Crack Depth with Surface Waves

There are two methods of determining crack depths with surface waves: intensity method and time delay method. A shortcoming of the intensity method is that the depth of the crack measurement is limited only to the range $d \leqslant 2\lambda$ (λ is wavelength and d is crack depth); a shortcoming of the time delay method is its inability to determine the vertical distance h (the crack depth) of the crack tip from the surface.

Measurement of crack depth with slant probe**

In this method, mainly the amplitude of crack reflection waves and the wandering range of the waveform are used to

*Li Keming, Liu Derong, and Li Jianmin et al participated in the research on this subject.
**The vertical dimension of crack formation from a nondetection surface to the detection surface is called the crack depth.

determine crack depth. A shortcoming of this method is the limited range of crack depth measurement. Generally, the limiting value is about 5mm. Because when the crack depth is greater than the limiting value, the amplitude of the reflection wave tends to saturation.

To rectify the shortcomings of the above-mentioned methods, the authors proposed using the creep wave reflection, lateral wave focusing tip echo method and the sound shadow method to measure crack depth and height. After testing and on-site applications, errors of the analytical values and measurement values are not greater than 12%. The three methods mentioned in this paragraph can be coordinated with the above-mentioned surface wave intensity and lateral wave intensity method. In a general situation, any crack depth can be determined with high precision.

Crack Depth Measurements with Creep Wave Probe

A property of creep waves is the propagation downward from the surface; therefore, the propagation is not affected by the degree of surface finish. The detected crack depth is determined by chip diameter D and probe frequency f. Designed by the authors' research team, the creep wave probe can be used to detect cracks of 1-9mm. For cracks of different depths, there are different sound pressure distribution curves, as shown in Fig. 1 (the sound pressure distribution is indicated with a relationship curve in which the height of the reflection wave of the crack varies with the distance from the front edge of the probe to the crack position). In addition, there is a maximum value for the amplitude of creep wave reflection for different crack depths; the sound path length of the maximum value is different for different crack depths, as shown in Fig. 2. Based on this rule in actual flaw detection, simultaneously with the sound pressure distribution for crack measurement, the sound path

length for the maximum value of the reflection wave height can be determined. From Fig. 2, the crack depth can be obtained. If there is curvature for the examined object, the creep wave probe with the corresponding curvature can be used

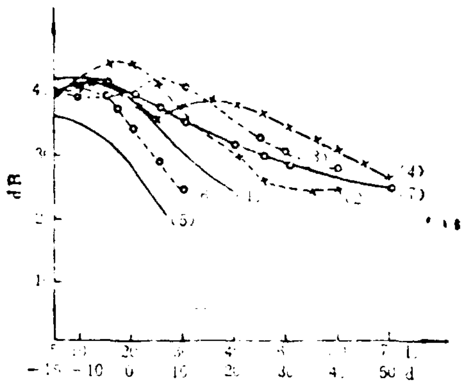

Fig. 1
Remarks: CST-3 instrument conditions: limited to the prescribed position at emission Reference block: 15, 16, and 25 L - transverse mark of fluorescent screen d - horizontal distance from crack to front edge of probe; for a penetration wave, d is one-half of the distance between the front edge of the receiving probe and the front edge of the emitting probe de: crack depth (7) penetration wave received that corresponds to C-6-2 blunt edge after emitting C-6-1 (1) corresponding to de3 (2) corresponding to de5 (3) corresponding to de7 (4) corresponding to de9 (5) corresponding to de1 (6) corresponding to de1.5

The problem of crack positioning is determined by the sound path of the reflection wave of the crack because the propagation speeds of a creep wave and a longitudinal wave are similar in value; first, a straight probe is used to adjust the scanning speed of the flaw detection instrument to 1:1. Then a pair of creep wave probes is used by employing the chip at the front of a probe as the emission; the chip, behind another probe, is used as the receiver. When the front edges of two probes are aligned, adjust the horizontal knob of the flaw detection instrument so

that the sound path of the penetration wave stops on the lateral mark 20 on the fluorescent screen. Then, the scanning speed is considered to have been adjusted. When measuring cracks, if the sound path of the reflection wave of the crack appears at the lateral mark 20 on the fluorescent screen, at that time the crack is just aligned with the front edge of the probe. When the probe is moved, the sound path of the reflection wave of the crack appears at the lateral mark 10; at that time, the crack is beneath the probe, and at a distance of 10mm from the probe's front edge.

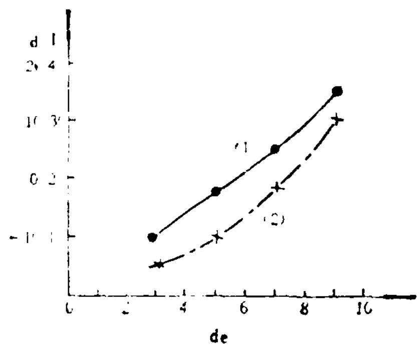

Fig. 2
Remarks: CST-3 instrument conditions: intermediate emission intensity with slightly restrained scanning speed L:d=1:1 L: the maximum value of the transverse mark on the fluorescent screen corresponding to the most remote signal d: the horizontal distance from the crack to the blunt edge of probe de: crack depth
(1) corresponding to axial-direction inspection
(2) corresponding to circumferential-direction inspection

Measurement of Crack Depth and Height by Using Tip Echo Wave Method

When a focusing probe is used, it is required that the depth at the top of a crack should be within the range of the focal column depth of the focusing probe. The crack depth or height is greater than 5mm.

1. When the detection surface is a plane

(1) When the crack develops from the examination surface, the scanning speed should be well adjusted according to depth. For a crack vertical to the surface, the sound path of the echo wave of the crack tip is the crack path (represented by d). If the scanning speed is adjusted according to the sound path, the crack depth $d = W \times \cos\beta$ (W is the echo sound path of the crack tip; β is the reflection angle of the probe), as shown in Fig. 8.

(2) When the crack develops from a nontest surface (as shown in Fig. 4), the crack height $h = T - W\cos\beta$.

(3) For cracks at the mid-portion of the examined object (as shown in Figs. 5 and 6), the crack height $h = (W_2 - W_1) \times \cos\beta$.

2. When the examined surface is a convex surface

In this situation, a focusing slant probe with the corresponding curvature is adopted to examine the crack height (depth), as shown in Figs. 7 and 8.

(1) When the crack develops from the examined surface, only by examining the sound path W of the echo wave of the crack tip, can the following formula be used to calculate the crack depth.

$$d = R - [(R - W \times \cos\beta)^2 + (W \times \sin\beta)^2]^{\frac{1}{2}}$$

In the equation, R is the radius of curvature of the examined surface.

(2) When the crack develops from a plane not being examined, similarly only the sound path W_1 is measured, can the following formula be used to calculate crack height:

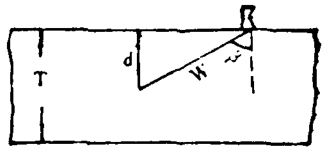

Fig. 3

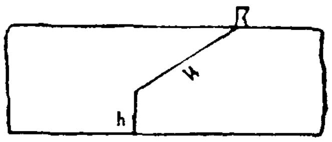

Fig. 4

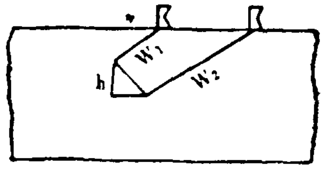

Fig. 5

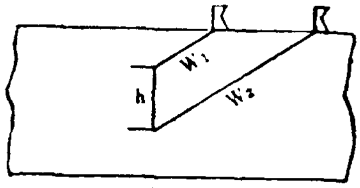

Fig. 6

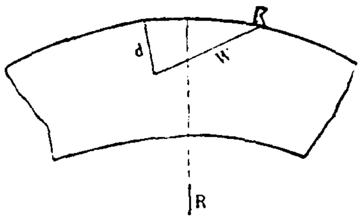

Fig. 7

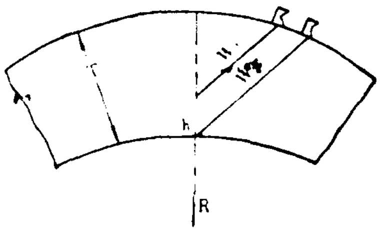

Fig. 8

$$h = T - \{R - [(R - W_1 \times \cos\beta)^2 + (W_1 \times \sin\beta)^2]^{\frac{1}{2}}\}$$

In the equation, T is the thickness of the examined workpiece.

In actual detection, frequently the sound path W_2 of the

reflection of the crack root is first detected; then the probe is moved forward to search for the echo signal of the crack tip. In this situation, the precise thickness of the workpiece is not required to be measured. The following formula can be used to calculate directly the crack height.

$$h = [(R - W_1 \times \cos\beta)^2 + (W_1 \times \sin\beta)^2]^{1/2} - [(R - W_2 \times \cos\beta)^2 + (W_2 \times \sin\beta)^2]^{1/2}$$

3. When the examined surface is concave

(1) When the crack develops from the examined surface, a focusing probe with the corresponding curvature can be used to measure the sound path W of the reflection wave of the lower tip of the crack. The following formula can be used to calculate the crack depth:

$$d = [(W \times \sin\beta)^2 + (W \times \cos\beta + R_{in})^2]^{1/2} - R_{in}$$

In the equation, R_{in} -- internal radius of the concave surface.

(2) When the crack develops from a nonexamined surface (as shown in Fig. 9), first the sound path W_2 of the reflection wave height at the root of the crack is detected, then the probe can be moved forward to measure the sound path W_1 of the echo wave at the crack tip. The following formulas can be used to determine the crack height:

$$h = [(W_2 \times \sin\beta)^2 + (W_2 \times \cos\beta + R_{in})^2]^{1/2} - [(W_1 \times \sin\beta)^2 + (W_1 \times \cos\beta + R_{in})^2]^{1/2}$$

or

$$h = T - \{[(W_1 \times \sin\beta)^2 + (W_1 \times \cos\beta + R_{in})^2]^{1/2} - R_{in}\}$$

In the equation, T -- thickness of the examined workpiece.

By using the echo wave method for the crack tip to measure crack depth and height, the measurement error is smaller than 10%. Before detection, the scanning speed of the instrument should be adjusted. The reflection angle of the probe and the

thickness of the examined workpiece should be measured precisely; in addition, the radius of the examined workpiece should be measured precisely. Thus, precision in measuring the crack height can be ensured.

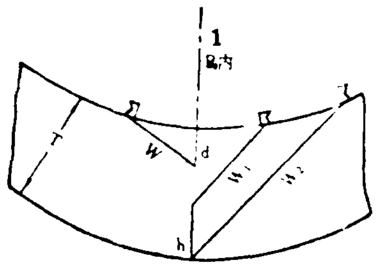

Fig. 9
KEY: 1 - R_{in}

The amplitude of the tip echo wave is relatively small, smaller by 20dB than the amplitude of the reflection wave at the terminal angle of the crack root. Therefore, for steel casting especially for coarse crystalline material, sometimes the echo signal of the crack tip and the noise signal cannot be separated. In this situation, the sound shadow method can be used to determine crack height.

Determination of Crack Height by Using Sound Shadow Method

1. When the examined surface is a plane (or in the case of axial-direction detection along a pipe section)

First, the number one probe (focusing probe) is used to measure the reflection signal of the terminal angle at the crack root. Move the probe and mark the sound path W when the reflection signal is the strongest. Then the main probe is fixed; mark on the corresponding workpiece at the rear of the probe. Then the number one probe is used for emitting a signal, and the number two supplementary probe (with the same parameters

and of the same model as the number one probe) is used to detect the signal for detection of a singly-emitted and detected signal (signal penetrating the crack). The operating state of the instruments is set at "Shuang" ("even"), as shown in Fig. 10. Move the number one probe so that for the singly-emitted and detected signal, the sound path $W_1=W$. Adjust the sensitivity and attenuation of the flaw detection instrument so that the signal height is 60%. Then the number of dB is N; for another attenuation of 5dB, that is, N+5dB; move forward the number one probe and push backward the number two probe. Only when the signal is at 60% and the sound path W, measure the distance L of probe motion. From the following equation, the crack height can be determined:

$$h=\frac{(L+\Delta L)}{tg\beta}$$

In the equation, β -- refraction angle of the number one main probe; and ΔL -- revised value (determined experimentally).

2. When the examined surface is a columnar surface (convex)

See Fig. 11.

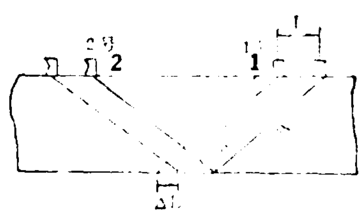

Fig. 10
KEY: 1 - Number one
2 - Number two

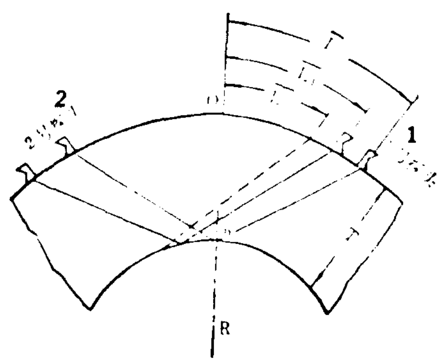

Fig. 11
KEY: 1 - Number one probe
2 - Number two probe

Use the focusing probe (main probe and supplementary probe of the corresponding curvature).

The key points of detection are identical with those described in (1). First, the number one main probe is used to detect the sound path W_1 of the reflection signal at the root of the crack. By using the following formula to calculate the arc length from the probe incident point to the corresponding position at the crack tip in order to determine point O, mark the crack position point O.

$$\widehat{L} = R\left(tg^{-1} \frac{W_1 \times \sin\beta}{R - W_1 \cos\beta} \right) \times 0.0174$$

In the equation: R -- radius of the external curvature of the examined workpiece;

β -- refraction angle of the main probe; and

W_1 -- sound path of the reflection signal at the crack root.

The operating state of the instrument is placed at "Shuang"; the number two probe is used for detection. Move the number two probe to allow the sound path to be equal to W_1; adjust the gain or the attenuation to adjust the signal to 60% height. Then 5dB is added; move the number one probe forward and pull backward the number two probe. When the sound path is equal to W_1 and the signal is at 60%, fix the number one probe. Measure the arc length $\widehat{L_1}$ from the point of incidence of the number one probe to the point O. $\widehat{L_1} - \widehat{\Delta L} = \widehat{L_3}$. In the equation, $\widehat{\Delta L}$ is the revised value, which is obtained experimentally.

Substitute $\widehat{L_3}$ into the following formula, then the crack height can be determined. $h = T - R + \frac{R\sin\beta}{\sin\left(\beta + \frac{\widehat{L}}{R} \times 57.296\right)}$

3. When the examined surface is concave (as shown in Fig. 12)

The examination procedure is identical to that of 2. When $\widehat{L_1}$ is measured, determine $\widehat{L_3}$. $\widehat{L_3} = \widehat{L_1} - \widehat{\Delta L}$

$$\text{Crack height } h = T + R_{in} - \frac{R_{in} \times \sin\beta}{\sin(\beta - \widehat{L_3}/R_{in} \times 57.296)}$$

In the equation, R_{in} -- the radius of internal curvature of the examined crude surface.

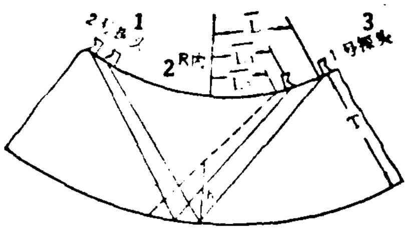

Fig. 12
KEY: 1 - Number two probe 2 - R_{in}
3 - Number one probe

Upon verification after analysis, the measurement error of the sound shadow method is not greater than 13%.

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